Spectroscopic Characterization of an Ultrashort Laser Driven Ar Cluster Target

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Intense ultrashort laser irradiated rare-gas cluster targets are of considerable interest due to their extensive x-ray emission in the keV energy range and their production of highly energetic electrons and ions. Such qualities have led applied scientists to consider these targets as debris-free x-ray sources for nanolithography and biological imaging as well as ion and neutron sources.

Spectroscopic modeling of intense ultrashort laser irradiated targets have predominately relied on steady state models with electron energy distribution functions (EEDF) composed of a low-temperature Maxwellian containing the bulk of the free electrons with a high temperature component constituting a small fraction of the total population. Though this type of model has been successful at describing the effects of hot electrons on the x-ray spectra, it relies on the unrealistic assumption that the EEDF is in steady state.

In this work, a coupled electron kinetic and collisional-radiative model [1] has been used to describe the time evolution of the EEDF, level populations, and x-ray spectra beginning immediately after the end of the main laser pulse and ending at an estimated time when the density of the expanding cluster is expected to fail to produce, to any spectroscopically significant amount, He- and Li-like transitions in the He_α spectrum. This period of time will be referred to as the after glow phase (AGP).

Experimental spectra were obtained in a collaborative experiment performed at the Advanced Photon Research Center, JAERI in Kyoto, Japan under the direction of Yuji Fukuda and Anatoly Faenov. A Ti:sapphire laser with an intensity of 1 x 10^{19} W/cm^2, a main temporal pulse width of 30 fs, and a 10-ns, 1 x 10^{14} W/cm^2 prepulse was focused on a Ar cluster gas jet. He-like spectra of Ar, including the associated satellites were recorded [2].

The time history of the irradiated cluster has been considered to evolve in three phases (Fig. 1). Beginning with a cold target, a 10-ns prepulse transforms the cluster into a moderately dense plasma: we assume the system is left in a Ne-like plasma state with a free-electron temperature of ~140 eV. Doubly-excited states in the Li-like spectral features suggest that the high energy electrons produced by the main pulse, and not the low energy electrons produced by the prepulse, are responsible for ionizing the plasma through the L-shell series of ions.

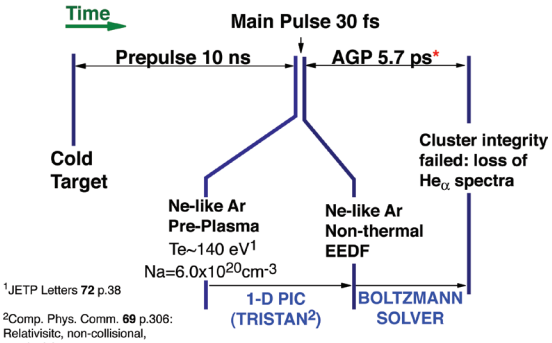


Fig. 1.
This diagram describes the evolution of the ultrashort laser driven Ar cluster target and the techniques used to model the different temporal stages.

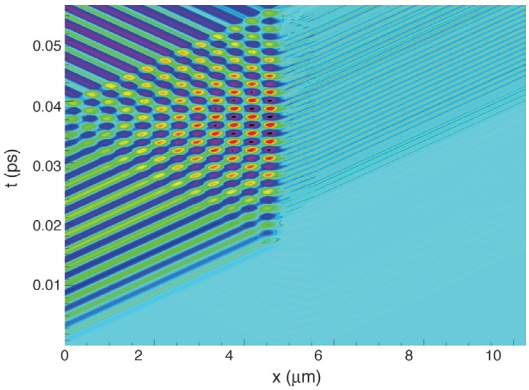
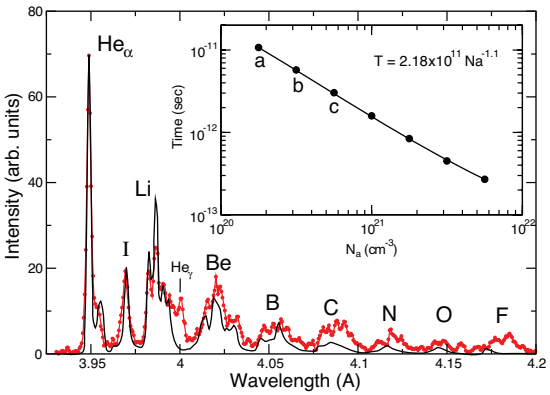


Fig. 2.
TRISTAN PIC simulation of the electric field due to the main laser pulse interacting with a cluster target placed between 4.5 and 5.5 microns. Laser pulse (approaching the target from the left) is predominantly reflected. Only a small component is transmitted (right half of image).



During the interaction of the main laser pulse with the cluster target, the EEDF was shown, by one-dimensional particle-in-cell (PIC) simulations with the TRISTAN code [3], to be driven far from a Maxwellian distribution as seen in the solid red line of Fig. 4. However, the PIC simulation with a reported core cluster electric field of E = 1 x 10^{10} V/cm, Fig. 2, was too small for tunneling ionization [4] to drive the ionization balance from the initial Ne-like Ar state.

A coupled electron kinetic and collisional-radiative model (Boltzmann Solver) was used to model the AGP phase of the irradiated cluster. The model included 3000 fine-structure levels spanning the Ne-like to He-like ionization stages with atomic configurations up to principle quantum number n = 3, and all x-ray transitions from n = 2 to n = 1 within the n = 3 manifold.

With the initial AGP EEDF taken from the TRISTAN code, the Boltzmann solver was run for a large number of cases, where the ion number densities and cluster integrity times were allowed to vary. This set of calculations resulted in the production of synthetic x-ray spectra such as the one seen in Fig. 3. A least squares fitting procedure of the synthetic to experimental spectra was performed as a coarse survey to limit the number of acceptable ion density, integrity time pair candidates. Further analysis comparing the ratio of the line intensities between the He_α and intercombination line (I), Fig. 3, revealed the proper ion density and integrity time to be Na = 3.162 x 10^{20} cm^{-3} and T = 5.7 ps respectively for this experiment.

The evolution of the EEDF during the AGP is shown in Fig. 4. Interestingly, by the end of the predicted AGP (cluster integrity time of 5.7 ps), the EEDF is still very far from the steady state result and the pseudothermalization of the free electrons is predicted to occur much later (after T = 27.0 ps). Through the use of the above time-dependent kinetic model we have obtained a realistic description of the evolution of an ultrashort laser irradiated cluster. This technique will allow exploration into the possibility of producing table-top x-ray sources with temporal pulse widths in the 100s of femtosecond time scale critical for studying ultrafast processes.

Fig. 3.
Synthetic (black line) and experimental (red points) time integrated He_α and satellite spectra for Case b: Na = 3.162 x 10^{20} cm^{-3}, T = 5.7 ps is shown. Insert contains least squares best fit for different Na and their corresponding AGP termination times.

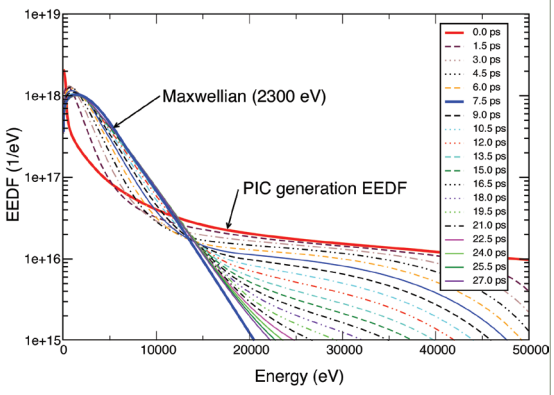


Fig. 4.
The time history of the EEDF for time after the end of the main laser pulse (AGP), computed for Na = 3.162 x 10^{20} cm^{-3}.

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